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ALTERNATIVE CONCEPTIONS OF COMMON SALT HYDROLYSIS AMONG UPPER-SECONDARY-SCHOOL STUDENTS

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Abstract. *Reactions in aqueous solutions are an important part of chemistry education. As experience shows, they are particularly difficult for students to understand. Hydrolysis is one such reaction. It occurs in organic and inorganic compounds with either covalent and ionic structures, but salt hydrolysis is a special example. Salt hydrolysis is complex, and to understand it, students must consider the reaction equilibrium, dissociation process, and acid-base properties of reactants and products. Additionally, in the upper-secondary-school curriculum, hydrolysis is described only qualitatively, which can lead students to misinterpret hydrolysis and solution equilibrium.*
In this study, 235 upper-secondary-school students answered questions about the acidity of common salt solutions and tried to justify their responses by writing appropriate chemical equations. An analysis of the answers revealed the students' alternative conceptions and misconceptions. The character of the misconceptions showed that they are school-based and largely caused by excessive simplification of the process as well as the usage of inappropriate analogies.
Key words: *salt hydrolysis, acids and bases, alternative and misconceptions, chemical education research.*

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Introduction

One of the principal factors that influence student learning is what they already know (Ausubel, Novak, & Hanesian, 1978). Their knowledge takes shape based on sensory impressions, cultural environments, peers, and the media, as well as classroom education (Chandrasegaran, Treagust, & Mocerino, 2008). Unfortunately, their understanding of newly acquired concepts can differ from what is scientifically acceptable (Damanhuri, Treagust, Won, & Chandrasegaran, 2016). Obstacles can arise, particularly if the new information is inconsistent with, or contrary to, prior knowledge and experience (Damanhuri et al., 2016; Jonassen, 1991; Resnick, 1983). Studies have demonstrated that some students tend to reject explanations that contradict their beliefs and that they prefer to retain a flawed notion that makes sense to them (Stepans, Beiswenger, & Dyche, 1986). According to Bodner (1986), knowledge conveyed by teachers should correlate with the previous conceptions and experiences of students. Bradley and Mosimege (1998) emphasise that teachers should focus on both the students' and their own misconceptions as well as gaps in definitions because teachers play a fundamental role in shaping student knowledge. All misconceptions, which are largely the result of inaccurately and accidentally developed knowledge, affect subsequent generations of students who, having been misled, make the same mistakes, thus remaining inconsistent with scientific concepts (Bradley & Mosimege, 1998). Understanding the essence of concepts is an indispensable factor in determining teacher progress. Through it, the teacher can properly organise the teaching process, plan learning steps, and develop and introduce simplified models. (Tiberghien, Jossem, & Barojas, 2001; Eichinger, Abell, & Dagher, 1997; Furió-Más, Calatayud, Guisasola, & Furió-Gómez, 2005). Therefore, it is crucial to identify misconceptions in various sectors of the chemistry curriculum and to guide teachers and students in the correct direction (Chandrasegaran et al., 2008; Kolomuç & Çalık, 2012; Sunyono, Tania, & Saputra, 2016).

Subjects related to reactions in aqueous solutions are difficult for upper-secondary-school students (Damanhuri et al., 2016). Many studies have shown that understanding acid-base concepts is especially difficult (Cros et al., 1986; Demerouti, Kousathana, & Tsaparlis, 2004a, 2004b; Lin, Chiu, & Liang, 2004; Nakhleh & Krajcik, 1994; Ross & Munby, 1991) and that students can often misinterpret them (Bradley & Mosimege, 1998; Chiu, 2007; Damanhuri et al., 2016; Nakhleh & Krajcik, 1994; Pinarbasi, 2007; Ross & Munby, 1991; Schmidt, 1991; Tümay, 2016). Hydrolysis is one of the most important subjects within the field of acid-base reactions and is the source of many misconceptions (Calik & Ayas, 2005; Demircioğlu, 2009; Seçken, 2010). When Pinarbasi (2007) asked his students: "*What is hydrolysis? Explain your answer as carefully as you can*", 73% of the students replied: *"Hydrolysis is the separation of matter into its ions by water",* thus mistaking the concept of hydrolysis for the process of dissociation (Schmidt, 1991). This error can be attributed to the literal interpretation of the term *hydrolysis* (Chu & Hong, 2010), as derived from the Greek *hydro* meaning water and *lysis* meaning disengagement, or loosening.

Hydrolysis was first mentioned in an article by Armstrong and Miller (1884) devoted to sulfonic acids. Hydrolysis can be defined as s*olvolysis by water,* where solvolysis is *a reaction with a solvent or with a lyonium or lyate ion involving the rupture of one or more bonds in the reacting solute* (McNaught & Wilkinson, 1997). Hydrolysis is more common than other types of solvolysis because of frequently occurring reactions in aqueous solutions and because, as it is an amphiprotic compound (Reichardt & Welton, 2010), water can easily be a Brønsted acid or a Brønsted base. Both organic and inorganic compounds can be hydrolysed.

Research Problem

Understanding the salt hydrolysis reaction is particularly difficult for upper-secondary-school students. They have problems with correctly describing the processes of dissolution and the reactions of ionic compounds with water, including writing the correct chemical equations. There is also a large discrepancy in the interpretation of these processes. It must be emphasised that the chemistry curricula at the upper-secondary-school level in Poland (MEN, 2012) as well as in international programmes (e.g., IBO, 2014) do not include quantitative descriptions of hydrolysis. However, students should be able to provide a qualitative description of the process and use it when discussing the acidity of salt solutions.

Research Focus

The aim of this research was to identify and characterise alternative conceptions of salt hydrolysis among upper-secondary-school students. It should also provide information about possible sources and causes of misconceptions on this topic that might be interesting and useful for chemistry teachers and educators. Taking this into account, this research addresses the question *"What are alternative conceptions of common salt hydrolysis among upper-secondary-school students?"*

Research Methodology

General Background of Research

This research used an analysis of textual data (Johnston & Toplis, 2012) based on student answers to fixed questions. It was conducted among upper-secondary-school students who are particularly interested in chemistry and were participants in the final (3rd) stage of a chemistry competition in the south of Poland. The competition differed from the Chemical Olympiad in that the required range of knowledge and skills conformed to the national core curriculum. The competition has become a tradition, as it has been organised for 35 years, and more than 1000 students participate in it each year. Laureates of the competition are admitted to chemistry studies at the Jagiellonian University without an entrance examination.

Participants

The research was conducted during the spring semester of the 2015/2016 academic year. The research sample consisted of 235 participants, 87 males and 148 females. All participants were 17 to 18 years old, attended a 2nd class upper-secondary-school (equivalent to the 11th grade) and pursued an extended chemistry course (its level

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is comparable with the extended-level of International Baccalaureate (IBO, 2014) and Advanced Placement (AP, 2014) programmes).

The aim of this research was to gather information on various interpretations of the hydrolysis process, rather than on its basic understanding. For that reason, this research was not carried out in a regular classroom, but among students participating in the competition, who were especially interested in chemistry. The sample contained participants from 48 schools throughout the region.

The participation of students from various schools, taught by different teachers, ensured that the results were not influenced by teaching style or by the understanding and interpretation of the phenomena by individual teachers. Moreover, it can be assumed that the chemical knowledge and scientific understanding of the participants was at the upper-secondary-school level because the scope of the competition did not force them to study extracurricular issues.

The research subjects were anonymous. Participants accepted the conditions of the competition and were aware that their tests could be used for qualitative and quantitative analyses.

Instruments and Procedures

The research was based on a question that was one of four competition tasks. The question consisted of four sub-samples. Each sub-sample involved a different type of salt solution, and the task had two parts. The students were first asked to state the acidity of a given salt solution (descriptive answers were required, not pH values) and then asked to verify this statement by writing down the appropriate chemical equation. The task was as follows:

Small amounts of selected solid salts (a-d) were added to 4 separate beakers with distilled water and mixed vigorously. The acidity of the solutions is to be tested.

I. *State the acidity of the tested solutions.*
II. *For each solution, write down the appropriate chemical equation to justify your statement or state that there was no reaction.*

The salts are:

a) Na_2CO_3 b) $ZnCl_2$ c) $MgCl_2$ d) $Cr_2(SO_3)_3$

The students had chemical booklets at their disposal, in which all of the salts in question were described as easily soluble in water.

Data Analysis

The student questionnaires were subjected to qualitative and quantitative analyses. Coding was used as a process of organizing and sorting data. At the first stage, qualitative analysis of completed questionnaires was performed. To this end, a list of codes was created that covered the identified characteristic features of the responses. The codes were divided into two parts: 1st – a statement on the acidity of the salt solution and 2nd – the characteristics of the written chemical equations. Then, student answers were coded into an Excel spreadsheet using a 0/1 coding system (1 – indicates the presence of a feature and 0 – indicates the absence of a feature), and the correlation coefficients and percentage frequencies of the answers were calculated.

The reliability of the data was checked using the intra-rater and inter-rater tests (Gwet, 2014). For this purpose, 25 randomly selected questionnaires were coded a second time by the main coding person and a third time by an independent researcher. The results were compared and the correlation coefficients were calculated. The correlation coefficient between the coding and re-coding was 0.95, $p<0.001$, and that between the coding and independent coding was 0.90, $p<0.001$. These results indicate high inter-rater and intra-rater reliabilities.

The Research Results

The student statements identified the acidity of the salt solutions as either acidic, basic, neutral or close to neutral. The frequencies of the answers are presented in Table 1.

Table 1. The frequencies of the answers on the acidity of the salt solutions.

Salt	Answers [%]				
	Acidic	Basic	Neutral	Close to neutral	No answer
Na_2CO_3 (Sodium Carbonate)	2	95	2	0	1
$ZnCl_2$ (Zinc Chloride)	92	1	5	0	2
$MgCl_2$ (Magnesium Chloride)	38	1	55	0	6
$Cr_2(SO_3)_3$ (Chromium(III) Sulfite)	8	4	68	8	12

Chemical equations written down by the students to justify their statements regarding the acidity of the solutions were analysed separately. Because the answers varied considerably, each sample has been described below in a separate paragraph.

The results for Na_2CO_3

For sodium carbonate, analyses of the reaction equations only consisted of examples in which the students described the basic character of the solution. Other statements were rather scant, and in most of these cases, no justification was presented. An analysis of the reactants written up by the students shows that the majority (75%) chose the reaction of carbonate ion with water (Table 2). This equation was usually preceded by an equation illustrating salt dissociation. The dissociation process was omitted by 25% of the students, while 11% of them wrote this equation with the sodium cation on both reaction sides and 14% of them wrote the chemical formula of the salt as Na_2CO_3 on the reactant side.

Table 2. The reactants and products written in the sodium carbonate hydrolysis equations and the frequencies of their occurrence.

Reactants	Products [%]				
	CO_2	$CO_2 \cdot H_2O$	H_2CO_3	HCO_3^-	Total
CO_3^{2-}	24	9	18	24	75
$2Na^+ + CO_3^{2-}$	7	2	2	0	11
Na_2CO_3	8	1	4	1	14
Total	39	12	24	25	100

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The equations written by the students differed not only in the reactants and products but also in the reaction arrow types. The frequency of the use of the reaction arrow types is presented in Table 3.

Equations 1 to 6 are the equations that were most frequently chosen by the students. Carbon dioxide was the most frequently mentioned product (39%), with 70% of those students using a one-direction arrow ($\rightarrow$) in the equation and 30% using both direction arrows ($\rightleftarrows$):

$$CO_3^{2-} + 2H_2O \rightarrow CO_2 + H_2O + 2OH^- \quad (1)$$

Formation of the bicarbonate ion was chosen by 25% of the students. In these instances, both-direction arrows ($\rightleftarrows$) appeared in 60% of the questionnaires, and this sign was more frequent in all of the following cases.

$$CO_3^{2-} + H_2O \rightleftarrows HCO_3^- + OH^- \quad (2)$$

Another 24% of the students placed the carbonic acid on the product side:

$$CO_3^{2-} + 2H_2O \rightleftarrows H_2CO_3 + 2OH^- \quad (3)$$

Whereas 12% of the students wrote the reaction product as $CO_2 \cdot H_2O$:

$$CO_3^{2-} + 2H_2O \rightleftarrows CO_2 \cdot H_2O + 2OH^- \quad (4)$$

Eleven percent of the students expressed the reaction in two stages:

$$CO_3^{2-} + H_2O \rightleftarrows HCO_3^- + OH^- \quad (5)$$

$$HCO_3^- + H_2O \rightleftarrows H_2CO_3 + OH^- \quad (6)$$

Table 3. Frequencies of right and both-direction arrows in the chemical equation for sodium carbonate hydrolysis.

Products	Arrows [%]	
	$\rightarrow$	$\rightleftarrows$
CO_2	70	30
$CO_2 \cdot H_2O$	41	59
H_2CO_3	32	68
HCO_3^-	28	72

The Results for $ZnCl_2$

Most students described the solution of zinc chloride as acidic (92%), and only the equations justifying that statement were analysed (Table 4). Additionally, most students (78%) wrote the zinc cation $(Zn^2)^+$ as a reactant in the hydrolysis reaction, and another 9% additionally put the chloride anion (Cl^-) on both reaction sides. The undissociated reactant in the form $ZnCl_2$ appeared in 13% of the questionnaires.

Table 4. The reactants and products written in the zinc chloride hydrolysis equations and the frequencies of their occurrence.

Reactants	Products [%]		
	$Zn(OH)_2$	$ZnOH^+$	Total
Zn^{2+}	63	15	78
$Zn^{2+} + 2Cl^-$	9	0	9
$ZnCl_2$	13	0	13
Total	85	15	100

In the hydrolysis reactions, two main products were identified: $Zn(OH)_2$ in 85% of the questionnaires or otherwise $Zn(OH)^+$

$$Zn^{2+} + 2H_2O \rightarrow Zn(OH)_2 + 2H^+ \quad (7)$$

$$Zn^{2+} + H_2O \rightleftarrows Zn(OH)^+ + H^+ \quad (8)$$

Moreover, it was found that when $Zn(OH)_2$ was a product, the one-direction arrow prevailed (59%), and for $Zn(OH)^+$, both-direction arrows prevailed (77%) (Table 5).

Table 5. Frequencies of right and both-direction arrows in the equation of zinc-chloride hydrolysis.

	Arrows [%]	
Products	→	⇄
$Zn(OH)_2$	59	41
$ZnOH^+$	23	77

The Results for $MgCl_2$

The magnesium chloride sub-sample was more challenging to students. They had trouble with both parts of the question: first, in deciding whether the solution was acidic or neutral (a basic solution was not indicated by the students), and then, in justifying the statement. Most students answered that the solution was neutral. In the justification, 63% noted that in this case hydrolysis did not occur, and 27% wrote a dissociation equation (9).

$$MgCl_2 \xrightarrow{H_2O} Mg^{2+} + 2Cl^- \quad (9)$$

The second-largest group (38%) answered that the salt solution was acidic. Analysis of the equations showed that students chose two reaction products – $Mg(OH)_2$ and $MgOH^+$ (Table 6).

Table 6. The reactants and products written in the magnesium chloride hydrolysis equations and the frequencies of their occurrence.

Reactants	Products [%]		
	$Mg(OH)_2$	$MgOH^+$	Total
Mg^{2+}	60	10	70
$Mg^{2+} + 2Cl^-$	9	0	9
$MgCl_2$	21	0	21
Total	90	10	100

Seventy percent of the students who described the solution as acidic put the Mg^{2+} ion on the reactant side, as shown in equations 10 and 11. Another 9% used the ionic notation with chloride anions on both reaction sides. The $MgCl_2$ notation appeared in 31% of the answers. An analysis of the frequency of the arrow types that were used is shown in Table 7.

$$Mg^{2+} + 2H_2O \rightarrow Mg(OH)_2 + 2H^+ \quad (10)$$

$$Mg^{2+} + H_2O \rightleftarrows MgOH^+ + H^+ \quad (11)$$

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Table 7. Frequencies of right and both-direction arrows in the equation of magnesium chloride hydrolysis.

Products	Arrows [%]	
	→	⇄
$Mg(OH)_2$	70	30
$MgOH^+$	25	75

The Results for $Cr_2(SO_3)_3$

In the case of $Cr_2(SO_3)_3$, students were to consider the hydrolysis of the anion and cation. The salt solution was described as neutral or close to neutral by 68% and 8% of the students, respectively. The equations justifying those answers were analysed. Only 6% of the students wrote one equation including the salt in its dissociated form (cations and anions). Another 6% put salt in the undissociated form – $Cr_2(SO_3)_3$ on the reactants side. In 88% of the questionnaires, the hydrolysis equations were preceded by a dissociation reaction and the reaction of the cation and the anion with water were written separately (Table 8).

Table 8. The reactants and products written in the chromium(III) sulfite hydrolysis equations and the frequencies of their occurrence, part A – cations.

Reactants	Products [%]			
	$Cr(OH)_3$	$Cr(OH)^{2+}$	$Cr(OH)_2^+$	Total
Cr^{3+}	72	13	3	88
$2Cr^{3+} + 3SO_3^{2-}$	6	0	0	6
$Cr_2(SO_3)_3$	6	0	0	6
Total	84	13	3	100

Three products were identified among the stated equations of the chromium(III) cation with water: $Cr(OH)_3$ – 84%, $Cr(OH)^{2+}$ – 13% and $Cr(OH)_2^+$ – 3%.

$$Cr^{3+} + 3H_2O \rightarrow Cr(OH)_3 + 3H^+ \quad (12)$$

$$Cr^{3+} + H_2O \rightleftarrows Cr(OH)^{2+} + H^+ \quad (13)$$

$$Cr^{3+} + 2H_2O \rightleftarrows Cr(OH)_2^+ + 2H^+ \quad (14)$$

One-direction arrows were predominantly used for $Cr(OH)_3$ (61%), whereas arrows in both directions were mainly used for $Cr(OH)^{2+}$ and $Cr(OH)_2^+$ (85% and 75%, respectively) (Table 9).

Table 9. Frequencies of right and both-direction arrows in the equation of the chromium(III) cation with water.

Products	Arrows [%]	
	→	⇄
$Cr(OH)_3$	61	45
$Cr(OH)^{2+}$	15	85
$Cr(OH)_2^+$	25	75

Considering the equations of the SO_3^{2-} anion with water, in half of them, the selected product was sulfurous acid (Table 10):

$$SO_3^{2-} + 2H_2O \rightleftarrows H_2SO_3 + 2OH^- \quad (15)$$

Otherwise, the HSO_3^- anion (24%), sulfur dioxide SO_2 (19%) and the hydrated form of sulfur dioxide $SO_2 \cdot H_2O$ (7%) were selected.

$$SO_3^{2-} + H_2O \rightleftarrows HSO_3^- + OH^- \quad (16)$$

$$SO_3^{2-} + 2H_2O \rightarrow SO_2 + H_2O + 2OH^- \quad (17)$$

$$SO_3^{2-} + 2H_2O \rightleftarrows SO_2 \cdot H_2O + 2OH^- \quad (18)$$

Some of the students (7%) wrote an equation for two-stage hydrolysis of the sulfite ion:

$$SO_3^{2-} + H_2O \rightleftarrows HSO_3^- + OH^- \quad (19)$$

$$HSO_3^- + H_2O \rightleftarrows H_2SO_3 + OH^- \quad (20)$$

Table 10. The reactants and products written in the chromium(III) sulfite hydrolysis equations and the frequencies of their occurrence, part B – anions.

Reactants	Products [%]				
	SO_2	H_2SO_3	HSO_3^-	$SO_2 \cdot H_2O$	Total
SO_3^{2-}	15	44	24	5	88
$2Cr^{3+} + 3SO_3^{2-}$	2	2	0	2	6
$Cr_2(SO_3)_3$	2	4	0	0	6
Total	19	50	24	7	100

When SO_2 or H_2SO_3 were entered as the main product, most students (68%) used a one-direction arrow (→), whereas with $HSO_3^-HSO_3^-$ as the product, arrows in both directions prevailed (Table 11).

Table 11. Frequencies of right and both-direction arrows in the equation of the sulfite anion with water.

Products	Arrows [%]	
	→	⇄
SO_2	68	32
$SO_2 \cdot H_2O$	59	41
H_2SO_3	68	32
HSO_3^-	28	72

Discussion

This research confirms that students at the upper-secondary-school level have difficulties in describing the salt hydrolysis process, even if those students are interested in chemistry. The first issue that becomes apparent when analysing the equations recorded by students is whether hydrolysis should be considered a property of the ions or of the salt. Most students wrote equations in which the ions reacted with water molecules. In this notation, the hydrolysis reactions were usually preceded by dissociation equations. It is apparent that the students saw the

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entire process as a sequence of events. This might have its origin in the syllabus or in the sequence in which these issues are discussed at school. In Poland, students learn about salt dissociation in lower-secondary school, when they first express reaction equations in the complete and net ionic form. Hydrolysis is discussed at the next stage of education. Moreover, during tests, students are usually required to answer and justify whether the solution is basic or acidic, rather than to describe the processes that occurs during the dissolving of a salt. Therefore, they focus on the reaction of a selected ion with water. This correctly identifies the acidity of a solution but can be misleading in regard to the definition of hydrolysis (solvolysis) because no bonds in the reactants are broken.

In the analysed question, the students' task was to consider hydrolysis of Na_2CO_3, $ZnCl_2$, $MgCl_2$ and $Cr_2(SO_3)_3$. In the case of the zinc chloride – a salt of a weak base and a strong acid - the students usually (correctly) stated that the solution was acidic (92%) and justified this statement with a reaction in which the product was zinc hydroxide $Zn(OH)_2$, i.e., an insoluble substance (S = 4.2 ·10^{-5} g/100 g H_2O, 20°C) (Haynes, 2014). Although the students did not assign any state symbol to the product formula explaining whether the compound was present in the solution (aq) or precipitate (s), the use of one-direction arrows ($\rightarrow$) in most cases indicated that the process was irreversible and that a precipitate of $Zn(OH)_2$ formed. (N.B. in chemistry education in Poland, two-direction arrows $\rightleftarrows$ are used to indicate that a reaction is reversible and to present an equilibrium process, but $\rightleftharpoons$ arrows are not used.) In a real laboratory situation, a zinc-hydroxide precipitate is observed when a large amount of the salt is added to water. In the case formulated in the question *"Small amounts of selected solid salts were added to….distilled water (…)"*, the result is a clear, acidic solution. Therefore, it is more appropriate to justify the acidity of the solution by citing the equations in which the product is an aquahydroxo complex of zinc (Arab, Bougeard, & Smirnov, 2003).

$$Zn^{2+} + 7H_2O \rightleftarrows [Zn(H_2O)_5OH]^+ + H_3O^+ \quad (21)$$

The essence of this process was reflected in the notation used by 15% of the students, who wrote the product as $Zn(OH)^+$, omitting the hydration of the zinc ion.

For the magnesium chloride solution, students found it difficult to correctly state the solution acidity. Most of them (55%) described the solution as neutral and justified this statement with the information that hydrolysis did not occur, or with the dissociation equations. This interpretation may originate from the claim found in many chemistry handbooks (e.g., Jones & Atkins, 2000) that hydroxides of the 1A and 2A group, except beryllium, form strong bases. However, this is contrary to observation: the pH of magnesium chloride solutions ranges from 5.0 to 6.0, which indicates that acidic hydrolysis occurs. This is what 38% of the students wrote. The majority declared magnesium hydroxide to be a product, while 10% cited the $MgOH^+$ ion. Of the students who selected magnesium hydroxide as a product, 70% used the one-direction arrow. This notation is analogous to that used for zinc chloride, but these two salts behave differently in solution. Adding magnesium chloride to water until the maximum solubility level is reached (S = 56 g/100 g H_2O, 25 °C) (Haynes, 2014) does not result in the formation of a magnesium hydroxide precipitate, although its solubility level is low (S = 6.9 · 10^{-4} g/100 g 20 °C) (Haynes, 2014). Therefore, the basic character of the solution can be justified by the following equation (22), which in fact is analogous to the description of zinc chloride in a diluted solution (21).

$$[Mg(H_2O)_6]^{2+} + H_2O \rightleftarrows [Mg(H_2O)_5OH]^+ + H_3O^+$$

$$[Mg(H_2O)_6]^{2+} + H_2O \rightleftarrows [Mg(H_2O)_5OH]^+ + H_3O^+ \quad (22)$$

The case of chromium(III) sulfite was the most difficult for students, as demonstrated by 12% of them giving no answer. A description of the process of hydrolysis for this substance is more complicated because the reaction of both the cation and anion with water should be considered. Because the strength of the acid and base formed in the process are different (pK_{a1}= 1.85, pK_b= 16.30 at 25°C) (Haynes, 2014), the solution is weakly acidic. However, the dissociation constants were not provided to students – neither in the question nor in the booklets – so the expected answer was 'close to neutral' – the answer given by 8% of the students. Most of them (68%) wrote that the solution was neutral due to the omission of the difference in the strength of the acid and base, but 34% claimed that *"hydrolysis did not take place"*.

To justify their acidity statements, students usually wrote separate equations with water as the anion and the cation (88%). Chromium (III) hydroxide was the most frequently mentioned product for the cation, whereas only 16% of the students decided the product of the reaction was $Cr(OH)^{2+}$ or $Cr(OH)_2^+$, including equations for two-stage hydrolysis (2%). The behaviour of the Cr^{3+} cation can be described in similar terms as Zn^{2+}, so the aquahydroxochromium(III) cation is formed at low concentrations (Reinhardt, 1966):

$$Cr^{3+} + 7H_2O \rightleftarrows [Cr(H_2O)_5OH]^{2+} + H_3O^+ \quad (23)$$

Insoluble chromium(III) hydroxide (S = 1.3 · 10^{-7} g/100 g 25ºC) (Haynes, 2014), seen as a green precipitate, is produced in higher concentrations, although, as in the case of $Zn(OH)_2$, chromium(III) hydroxide was not described as a solid (s), but most students who indicated it as a product used a one-direction arrow.

The equations for the reaction of the sulfite anion with water included the formation of sulfurous acid (50%), a hydrogen sulfite anion $HSO_3^-HSO_3^-$ (24%), sulfur dioxide SO_2 (19%), and – $SO_2 \cdot H_2O$ (7%). When considering these products, it should be noted that sulfurous acid is unstable and decomposes into H_2O and SO_2 (Otto & Steudel, 2000; Voegele, Tautermann, Rauch, Loerting, & Liedl, 2004). This fact was used by students who wrote sulfur dioxide as the product in the form of SO_2 or $SO_2 \cdot H_2O$. Whether SO_2 was aqueous or gaseous was not indicated. However, similar to the examples of zinc and chromium hydroxide precipitates, the use of one-direction arrows ($\rightarrow$) in 68% of the questionnaires for SO_2 implied that it was an irreversible process and a gaseous product was expected.

Use of the notation $SO_2 \cdot H_2O$ is quite surprising. We can assume that this is a way of representing an aqueous solution of sulfur dioxide (hydrate). However, this notation is, strictly speaking, incorrect. It is used to demonstrate that two tautomeric forms of sulfurous acid are present in an aqueous solution, H-S(=O)$_2$OH and $SO(OH)_2$, as well as their ions, HSO_3^- and SO_2OH^-, respectively (Otto & Steudel, 2000; Steudel & Steudel, 2009). However, the existence and stability of these molecules are not considered at the upper-secondary-school level, so this was most certainly not the students' intention. This is probably analogous to $NH_3 \cdot H_2O$, which emphasises that molecules in the form of NH_4OH are not present in aqueous solution (Hawkes, 2004), but this analogy is not correct for sulfur dioxide.

The equations describing the reaction of carbonate anions with water, justifying the basicity of the Na_2CO_3 solution, were similar to those describing the hydrolysis of sulfite ions. In this case, 24% of the students mentioned a product that does not exist in solution – carbonic acid (England et al., 2011) – and 12% of the students wrote it in the form $CO_2 \cdot H_2O$. Adding a small amount of Na_2CO_3 to water does not result in gas formation, so the ionic product, HCO_3^- (25% of the answers), as given in equation (2), can be regarded as the most correct. However, when a larger amount of Na_2CO_3 is added to water, carbon dioxide is produced by reaction (1). The students in this case consistently failed to describe the state of CO_2 ((aq) or (g)) formed in the reaction, so the interpretation could only be based on the arrows applied. The students in 70% of the answers used one-direction arrows, which suggested that the reaction was irreversible and a gaseous product would be formed.

The results for all four cases show there is a wide variation in the interpretation of the hydrolysis process, especially in the identification of products. The expressed hydrolysis equations very often reflected the pattern (25) used in school and academic handbooks, which is a great simplification.

$$acid + base \underset{hydrolysis}{\overset{neutralization}{\rightleftarrows}} salt + water \quad (25)$$

Applying this pattern to the salt solutions in the analysed question did not give fully correct answers, and the specified products were not consistent with the experimental results or real reaction products. Regarding the hydrolysis of specific salts, each example should be analysed separately, with a focus on the properties of specific substances that are hydrolysed. In terms of the behaviour of metal cations in aqueous solutions, it should be stressed that they are hydrated and form coordination ions with water molecules as ligands (Huheey, 1978; Mink, Németh, Hajba, Sandström, & Goggin, 2003; Wilkinson & Cotton, 1988):

$$M^{n+} + xH_2O \rightleftarrows [M(H_2O)_x]^{n+} \quad (26)$$

which are subsequently hydrolysed according to the following equation (Huheey, 1978; Wilkinson & Cotton, 1988)

$$[M(H_2O)_x]^{n+} + H_2O \rightleftarrows [M(H_2O)_{x-1}OH]^{(n-1)+} + H_3O^+ \quad (27)$$

This notation has an advantage over one with 'bare' metal ions on the reactants side because it is formally consistent with the definition of hydrolysis, which indicates that bonds in a reactant are broken. Moreover, omitting this process leads students to two common misconceptions:

1. The product is a hydroxide, which, in the case of insoluble metal hydroxides, should be observed as a precipitate and is often contrary to experimental observations.
2. The product is in the form $M(OH)_n^{m+}$, which is not consistent with the accepted knowledge about coordination compounds.

Referring to the reaction of anions with water, particular attention should be paid to multi-stage hydrolysis. In these cases, most of the students described the products as acids that are not present in solution or as oxides dissolved in water or emitted as a gas. It should be stressed that nearly all multi-proton acids, except sulfuric acid,

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are weak at all stages of deprotonation. When comparing the dissociation constants of these acids, it can be noted that their strength decreases as consecutive protons are lost, which means that the hydrolysis constant increases. Therefore, the first hydrolysis reaction should be cited (Jones & Atkins, 2000; Wilkinson & Cotton, 1988), e.g.:

$$CO_3^{2-} + H_2O \rightleftarrows HCO_3^- + OH^- \quad (5)$$

However, this does not mean that the second stage of hydrolysis does not take place, but that its significance is low.

$$HCO_3^- + H_2O \rightleftarrows H_2O + CO_2 + OH^- \quad (6)$$

The second stage of hydrolysis for carbonates can be significant at higher concentrations, which is observed as the formation of carbon dioxide gas bubbles.

Conclusions and Implications for Practice

In sum, this research confirmed that the concept of hydrolysis is difficult for upper-secondary-school students. They are usually able to correctly state the acidity of solutions of common salts, but writing chemical equations that explain the phenomena is a great challenge. Additionally, at this stage, most of the alternative misconceptions can be identified. The character and complexity of the student answers suggest that those misconceptions are school-based rather than brought about by the media, home or general knowledge. Some of them have their roots in misunderstanding the equilibrium processes, acids and bases, structure of matter and other basic issues. Additionally, students' tendency for using incorrect analogies is quite apparent. Another source of misconceptions is the lack of laboratory practice. Students have difficulties with the correct description of the processes and do not know if a precipitate is formed because of hydrolysis, if gases are involved or if there are no signs of the reaction visible to the naked eye.

Therefore, when introducing hydrolysis, teachers should try not only to explain precisely the processes and write the correct equations but also to link descriptions with authentic lab situations. Laboratory practice should not be reduced to merely examining the acidity of common salt solutions but should also include an analysis of the products in various concentrations as well as the identification of precipitates or gases. It is also important to clarify student answers. Teachers should require students to give full information in chemical equations so all reactants and products should include a state symbol (s, l, g, aq). That would not only spur students to consider their answers more thoroughly but also help teachers identify student misconceptions and the misinterpretation of processes. Finally, hydrolysis should not be introduced as simply the reverse process of the neutralisation reaction; cases of specific salts should be analysed separately, with an introduction of coordination ions when appropriate.

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